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Summary

In the first two months of this project, we have deposited a variety of amorphic diamond costings on various types of substrates including glass, copper, molybdenum and chromium. The films of various thicknesses have been deposited which are ready for testing. In addition, we have designed and constructed two low voltage test setups as well completed these tests for testing the high current emission properties of these films. These are described in this report.

Introduction to the Problem

There is a need for developing high current cathodes for e-beam pumped high power visible and near UV lasers. These applications require broad area cathodes which can provide current densities as high as 1000A/sq. cm for pulse durations of 1-5 microseconds at a repetition rates as high as 100 pulses/sec at voltages in the 100-500 kV range. These are very extreme requirements, but several cathodes such as thermionic cathodes, photo-electric cathodes and cold cathodes have been developed to deliver several tens of amperes/sq. cm current densities. This project concerns with the optimization of field emission cold cathodes using diamond materials.

From the standard Fowler-Nordheim equations governing field emission, it is concluded that the there are three key parameters which determine the total current from a broad area cold cathode:

(i) the effective field emission work function of the cathode,
(ii) the field enhancement factor (such as that for micro-tips), and
(iii) the number of emission sites per unit area.

From the F-N theory, it can be calculated that electron emission from metals with a typical work function of 4.5 eV requires an electric field in the 10^7 V/cm range, which is too high for almost all applications. The normalized electric field (and thus the applied voltage) can be lowered by taking advantage of the fact that electron emission from a sharp metal tip cathode occurs at a smaller applied voltage between cathode and anode. The reason for this is that the sharp metal tip draws the field lines towards the tip and the field at the cathode is much higher than the average field. The factor by which the field at the cathode is increased is refered to as the field enhancement factor (beta) and depends on the radius of curvature of the tip and tip height. This is the method due to which the current cold cathodes such as velvet cloth and graphite fiber emitters

are made to emit electrons at relatively low A-K electric field. Moreover, the total current density is increased due to very large number of fibers.

Large area cold cathodes based on the concepts described in the previous section are presently available and can deliver current densities in the several tens to several hundreds of amperes/square cm. range. The examples include velvet cloth fiber cathode, graphite fiber emitters and tantalum foil emitters. These cathodes suffer from the following problems.

(i) Diode Closure

(ii) Emission Site Density

(iii) Loss of Emission Sites

(iv) Non-Uniformity of Emission Sites

(v) Severe Outgassing

Solution to the Problem

From the discussion in a previous section, one can immediately see that diamond offers critical advantages in removing the heat from the emission sites due to diamond's large thermal conductivity, high thermal diffusivity and negative electron affinity.

In the previous section, we noted that in the FN equation, the exponent essentially governs the electron emission from the cathode. For a given emitted current density, the higher the barrier the greater the field required. Elemental metals (graphite and carbon too) have work functions greater than 4eV and rare earth borides greater than 2eV. Therefore, the fields required for useful current are greater than 2×10^9 V/m (2000MV/m) for flat metal cathodes, sufficient to cause all problems mentioned before. In the case of cold cathodes described in section IC, the electric field required was decreased by using sharp whisker type protrusions which use local field enhancement phenomenon to reduce the A-K field requirements to a value as low as 50kV/cm. Another method is achieve the same result is to use a cathode with a much smaller work function. Table 1 shows how a reduction in work function from 5 eV to 1eV can dramatically reduce the microscopic extraction field at a very moderate enhancement factor of 5. An enhancement factor of 5 corresponds to a relatively flat thin film, while the thin protrusions similar to carbon felt usually have a beta of several hundred.

Table 1: Microscopic Extraction Field Required at ONE Emission site (beta=5) as Function of Work Function at Various Current Densities

	10 A/cm^2	100 A/cm^2	1000 A/cm^2	10,000A/cm^2
Φ = 1.0	2.7 MV/cm^2	3.0 MV/cm^2	3.3 MV/cm^2	3.7 MV/cm^2
Φ = 2.0	8.16 MV/cm^2	9.0 MV/cm^2	10.1 MV/cm^2	11.4 MV/cm^2
Φ = 3.0	13.9 MV/cm^2	16.9 MV/cm^2	19.0 MV/cm^2	21.3 MV/cm^2
Φ = 4.0	23.7 MV/cm^2	26.4 MV/cm^2	29.3 MV/cm^2	33.0 MV/cm^2
Φ = 5.0	33.0 MV/cm^2	36.0 MV/cm^2	41.0 MV/cm^2	47.0 MV/cm^2

There are several materials which have low work functions. Diamond is one of these materials, which has a negative electron affinity in the (111) direction as shown in Figure 1. Negative electron affinity (NEA) is the energy difference between the conduction band and the vacuum level; while the work function is the energy difference between the Fermi level and the vacuum level. Thus, if the (111) diamond could be doped with n-type impurities, it will have a very low or even negative work function depending on the dopant level.

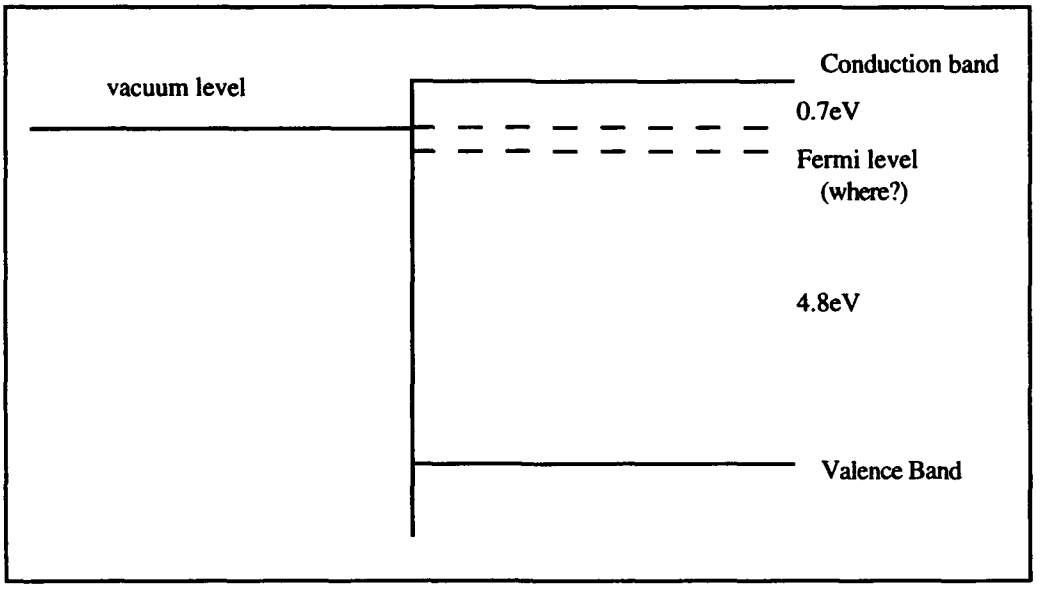

Figure 1: The energy band diagram of (111) diamond.

SI Diamond Technology, Inc., in collaboration with MCC (Microelectronics and Computer Technology Corporation, Austin, TX) has developed a totally new broad area diamond cold cathode based on amorphic diamond thin film deposition technology. Preliminary experimental data indicates that amorphic diamond films emit electrons at electric fields lower than 100kV/cm as compared to greater than 2,000MV/m for flat metal. A graph showing the diode like current voltage (IV) characterestics of a amorphic diamond cathode is shown in Figure 2. ***The maximum current density tested so far is about 10A/cm^2 continuous without cooling the anode or the cathode.*** *We expect much higher current densities when the anode and cathode are properly cooled.*

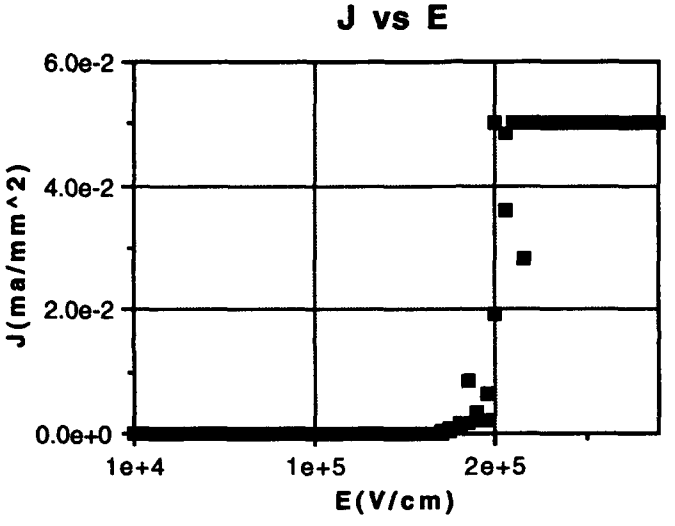

Figure 2: Diode like IV characterestics of a flat diamond graphite composite film (the current saturation is due to the power supply current limit set up to avoid over-heating)

Amorphic Diamond (AD) Thin Film Technology

The amorphic diamond (AD) fabrication technology was invented at University of Texas, Dallas by Dr. Suhas Wagal (Co-PI of this project) and Prof. Carl Collins (U.S. Patents #4,987,007 and 5,098,737) as a result of research funded by SDIO. SIDT has an exclusive license to this technology. The cold cathode properties of amorphic diamond were discovered and developed by Dr. Nalin Kumar (consultant in this project) at Microelectronics and Computer

Technology Corporation (MCC). This technology is protected by at least five patent applications at this time. SIDT has entered into collaborative agreement with MCC, so that SIDT has full rights to any further developments at MCC.

Figure 3 shows a schematic diagram of the AD deposition process. The laser ablation source consists of a pulsed Nd:YAG laser which ablates a graphite target. The ablation plume, which contains highly ionized and energetic carbon atoms, impinges upon the substrate to be coated, thereby creating a very hard, dense and amorphous film. Laser ablation deposition of AD on various materials including silicon, glass, various metals and polymers has been performed at room temperature. Thicknesses as large as 1.5 microns have been deposited over large areas (>2 inch diameter). We believe that we can apply this technique with other substrate materials to produce cold cathode films which are also hard, flexible, adherent films with additional beneficial properties, such as resistance to oxygen erosion.

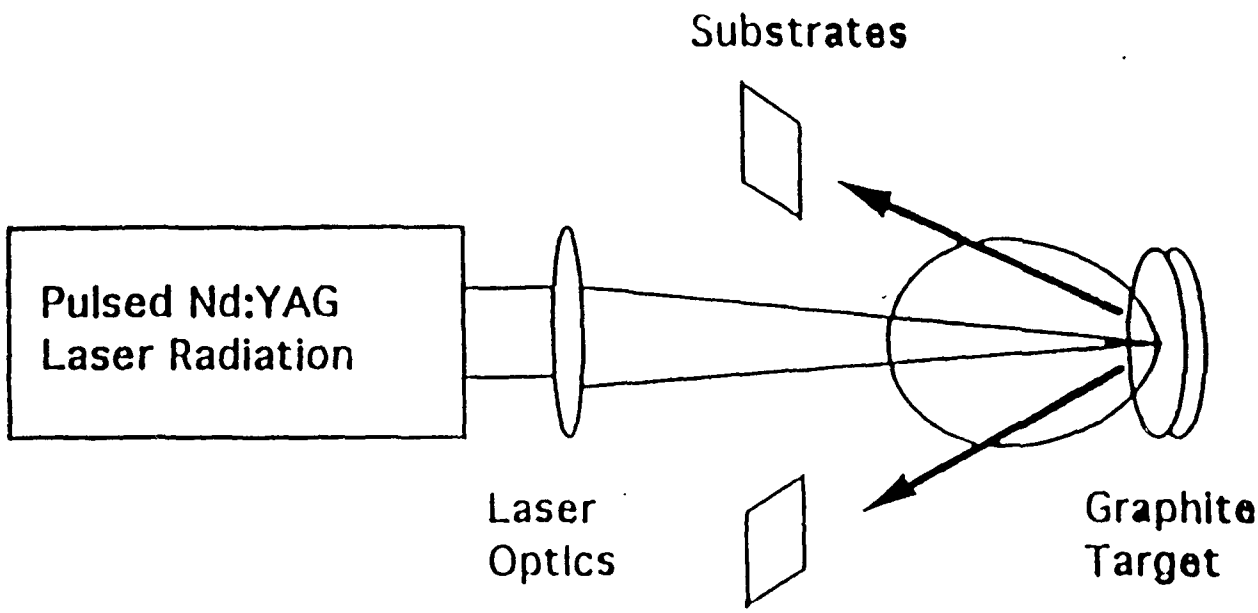

Figure 3: A schematic diagram showing the amorphic diamond fabrication process

Progress

In this reporting period, we have deposited a variety of amorphic diamond costings on various types of substrates including glass, copper, molybdenum and chromium. The films of various thicknesses have been deposited which are ready for testing. In addition, we have designed and constructed two low voltage test setups as well completed these tests for testing the high current emission properties of these films. These are described below.

DC Testing Setup #1:

This system is shown schematically in Figure 4. In this system, a small sample (typically 1 cm x 1 cm) coated with diamond film is mounted on a substrate holder. This holder is connected to an x-y-z-T manipulator mounted on a vacuum chamber. A very fine resolution z-axis

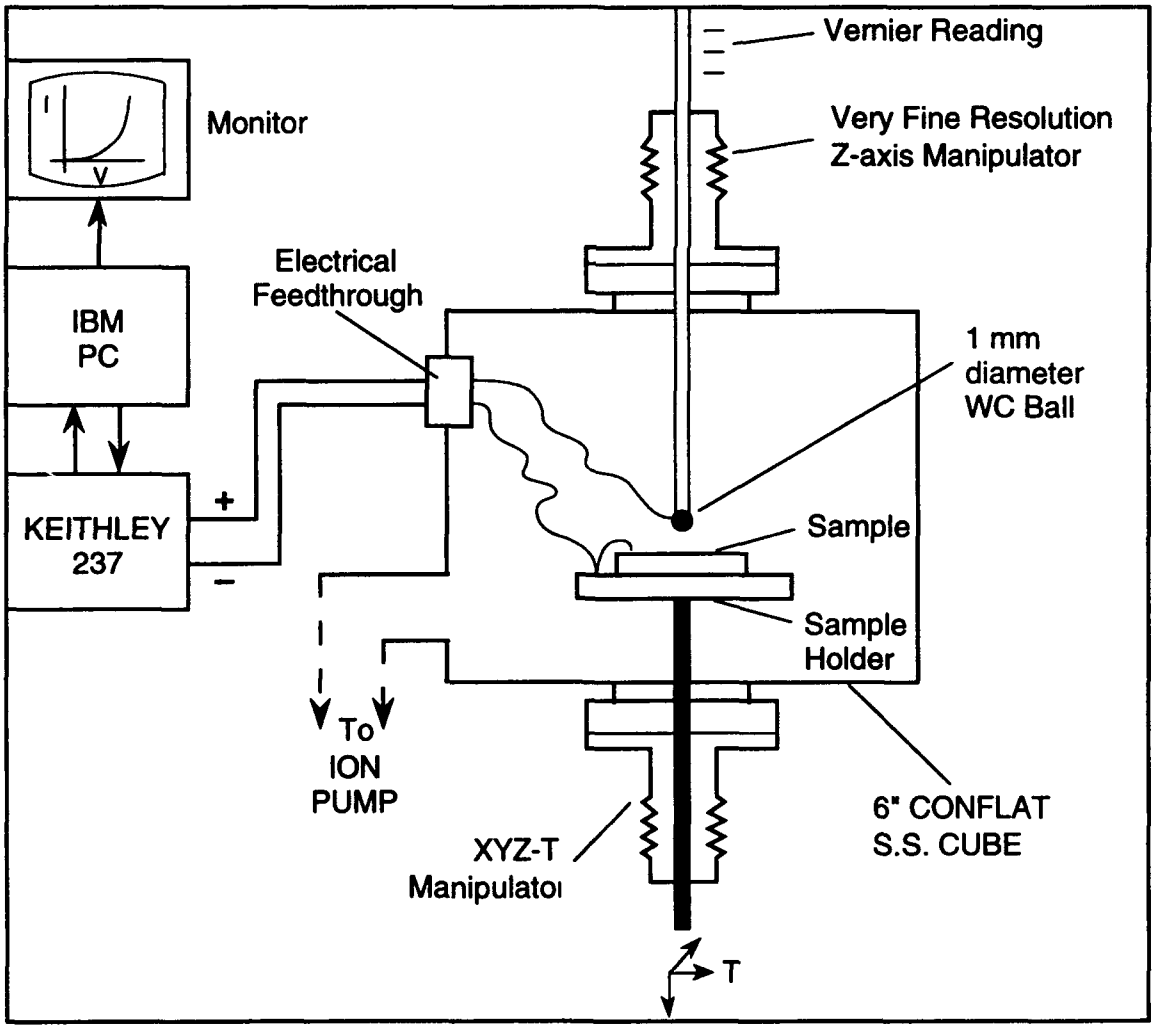

Figure 4. Ball probe tester

manipulator is mounted on the other side of the chamber as shown in Figure 4. A one mm diameter WC ball is attached to the z-axis manipulator (with a resolution of 0.2 microns) such that it can be brought into a close proximity of the sample. This A-K gap is typically 5–50 microns. A voltage is applied between anode and cathode by a Keithley 237 power supply controlled by an IBM personal computer. Current is measured and recorded as the voltage is changed by the computer. A typical I-V curve obtained is shown in Figure 2.

Knowing the area of emission from the geometry of the ball and the gap, a J-E chart can also be plotted. Unfortunately, there is an uncertainty in the effective area which results in the uncertainty in the current density. In addition, the A-K gap is not easily measured in the setup. These problems are solved in the next setup called FED 1.4 which is described below.

DC Testing Setup #2 (FED1.4):

The details of the FED 1.4 setup is shown schematically in Figure 5. It consists of a ceramic base with precision holes for 9 test rods and 3–4 spacer rods. The test rods are made of 0.25 mm diameter tungsten wire, while the spacer rods are made from typically 0.5 mm tungsten wires. By systematical polishing of test rods and spacer rods, we can make all the test rod surfaces in one plane which is around 15μ away from a parallel plane formed by the spacer rods. The gap can be measured either by a surface profilometer or by an optical microscope.

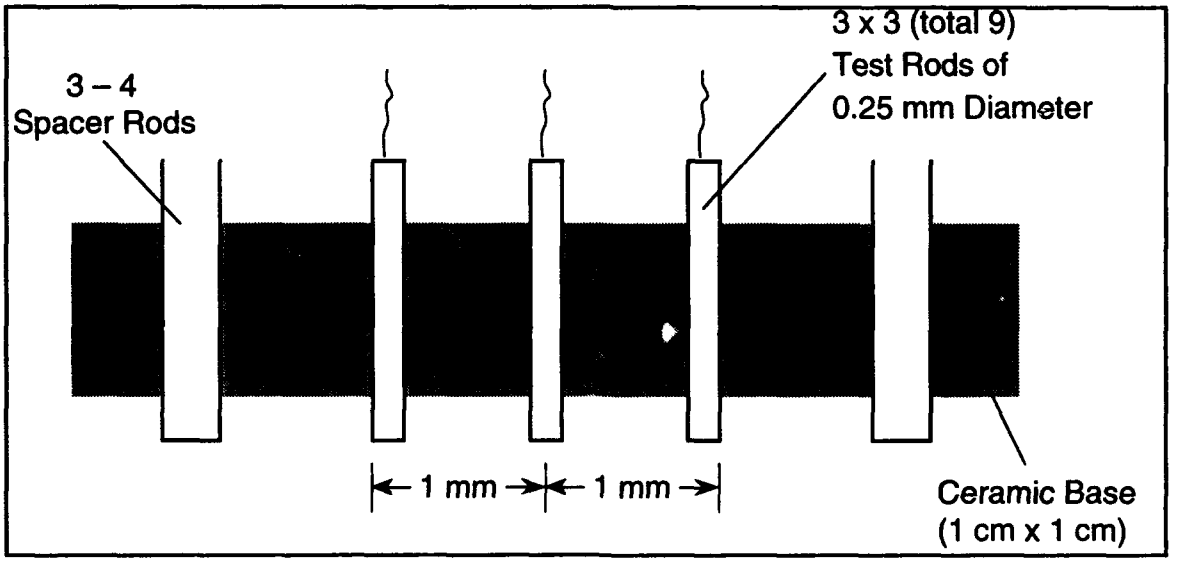

Figure 5. A two-dimensional view of a FED 1.4 tester head showing 3 x 3 array of 0.25 mm diameter test rods.

The above test head is mounted on a diamond coated sample and the whole assembly is placed in a vacuum chamber. This system has the advantage that the determination of the active area and the gap size is much more precise and multiple measurements can be done with one setup.

Figure 6 shows the relative voltage required as a function of time for our amorphic diamond to emit a DC current of 4mA/cm^2. In the graph, the beginning voltage is set to be 1. The absence of any dramatic rise in the relative voltage indicates the stability of the material at this current level.

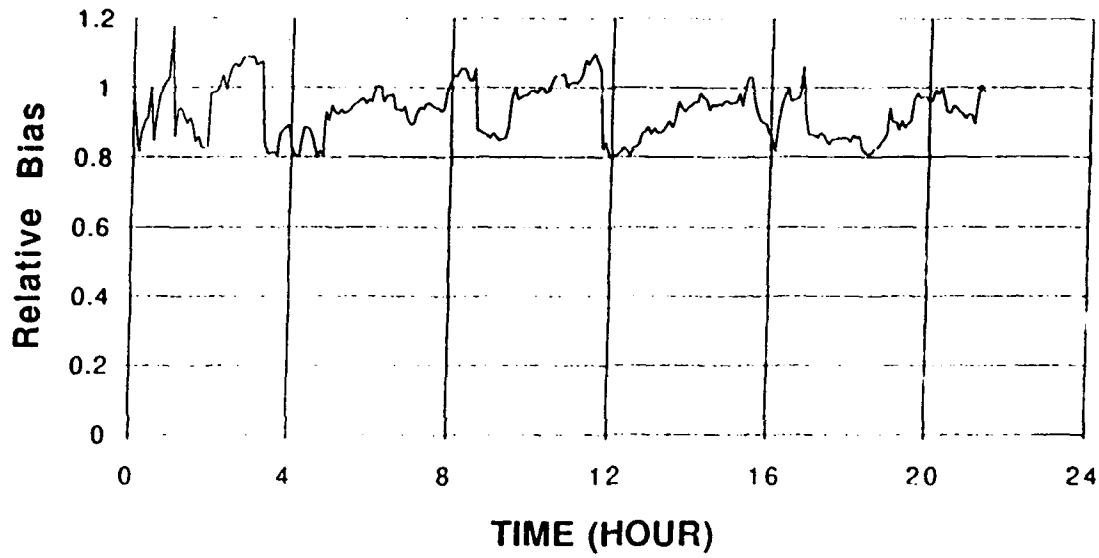

Figure 6: The relative voltage required as a function of time for our amorphic diamond to emit a DC current of 4mA/cm^2. The absence of any dramatic rise in the relative voltage indicates the stability of the material at this current level.

Problems Faced by the Project

We have found that the high power testing of samples is very difficult in Prof. Collins' lab at University of Texas, Dallas. This is expected to delay the project. We are in the process of locating alternate testing sites.

Schedule

Task 2 and Task 3 are on schedule and will be finished in the next two months. Task 1 has slipped and we are looking for alternate testing sites. We anticipate that the final report may be delayed by as much as two months.